

# Analysis and Design of Active and Passive Filter Circuits

## Analogue Electronics Laboratory 2

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## **Abstract**

This report presents the analysis and design of electronic filter circuits. The first part details the investigation of a passive RC low-pass filter using theoretical calculations, PSpice simulation, and experimental measurements. The second part extends these concepts to the design and simulation of a second-order active variable high-pass filter using a Sallen-Key topology. Theoretical and simulation results for the passive filter were in strong agreement, confirming a cutoff frequency of approximately 1.59 kHz, though experimental results deviated significantly. The active filter design demonstrates how op-amps and variable components can be used to create adjustable, real-world filter applications, and the simulation results are compared against theoretical predictions.

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# 1 Introduction

Passive filters are fundamental components in electronics, used to selectively pass certain frequencies while attenuating others. This report focuses first on the analysis of a first-order low-pass filter, constructed from a resistor and a capacitor. The objective is to understand and verify its frequency-dependent behaviour through three distinct methods: theoretical calculation, software simulation, and physical experimentation.

By comparing these results, this report validates the theoretical model, identifies key circuit characteristics like the cutoff frequency, and critically examines discrepancies between ideal models and physical implementation. The principles explored are then extended in the second part of the report to the design of a more complex **Variable High-Pass Filter**. This second-order active filter demonstrates how operational amplifiers and variable components can be integrated to create adjustable filters suitable for practical applications such as audio tone control.

## 2 Background

### 2.1 Passive Low-Pass RC Filter

A passive low-pass filter allows signals with a frequency lower than its cutoff frequency ( $f_c$ ) to pass while attenuating higher frequencies. For a simple RC circuit, the cutoff frequency is the point where the voltage gain drops by -3 dB and is defined as:

$$f_c = \frac{1}{2\pi RC} \quad (1)$$

For the circuit under test, with  $R = 10 \text{ k}\Omega$  and  $C = 10 \text{ nF}$ , the theoretical cut-off frequency is approximately **1591.5 Hz**.

### 2.2 Active Sallen-Key High-Pass Filter

Active filters use an active component, such as an operational amplifier (op-amp), to provide signal gain and buffering, overcoming the signal attenuation issues of passive filters. The circuit designed in this lab is a **second-order unity-gain Sallen-Key high-pass filter** [6]. The cutoff frequency is determined by two capacitors ( $C1, C2$ ) and two resistive paths, which are made adjustable by a dual-ganged  $10 \text{ k}\Omega$  potentiometer ( $VR1$ ). Based on the simplified ideal formula, the theoretical range of the cutoff frequency can be calculated:

- **Maximum Cutoff Frequency** ( $VR1 = 0 \text{ }\Omega$ ):  $R_{eff} = 3.3 \text{ k}\Omega$

$$f_{c,max} = \frac{1}{2\pi(3.3 \times 10^3 \text{ }\Omega)(22 \times 10^{-9} \text{ F})} \approx 2189 \text{ Hz} \quad (2)$$

- **Minimum Cutoff Frequency** ( $VR1 = 10\text{ k}\Omega$ ):  $R_{eff} = 13.3\text{ k}\Omega$

$$f_{c,min} = \frac{1}{2\pi(13.3 \times 10^3 \Omega)(22 \times 10^{-9} F)} \approx 543\text{ Hz} \quad (3)$$

The filter is therefore expected to have an ideal adjustable cutoff frequency ranging from approximately 543 Hz to 2.2 kHz.

## 3 Methodology

### 3.1 Low-Pass Filter

#### 3.1.1 Simulations

The Low-Pass Filter shown in Figure 1 was constructed in PSpice [1] using a sinusoidal voltage source ('VSIN') with a 10V amplitude, in series with a 10k $\Omega$  resistor and a 10nF capacitor. A transient analysis was run at 10 kHz and 100 kHz. The source was then changed to an AC type ('VAC') for an AC sweep simulation from 10 Hz to 10 MHz.

#### 3.1.2 Experimental Measurements

The physical circuit was built using discrete components on a breadboard. The Pico-scope's analogue waveform generator was set to output a sine wave with a target amplitude of 2V. The oscilloscope was connected to a PC to measure both input and output voltages across a frequency range of 0.5 kHz to 30 kHz.

### 3.2 Variable High-Pass Filter Design

The active high-pass filter shown in Figure 2 was constructed in PSpice using the 'LM741' op-amp model [7], powered by +12V and -12V sources. To simulate the dual-ganged variable resistor, a parameter 'RES1' was defined. Both instances of the variable resistor were set to 'RES1'.

A \*\*parameter sweep\*\* was then combined with an AC sweep analysis. The AC sweep was configured to run from 10 Hz to 100 kHz. The parameter 'RES1' was swept through key values to represent the potentiometer's positions:

- Minimum resistance: 1  $\Omega$
- Mid-point resistance: 5 k $\Omega$
- Maximum resistance: 10 k $\Omega$

This process generates three separate frequency response curves on a single plot, demonstrating how adjusting the potentiometer affects the filter's cutoff frequency.

## 4 Results

### 4.1 Low-Pass Filter

#### 4.1.1 Simulation Results

The AC sweep simulation for the passive filter confirmed a cutoff frequency of **1.6 kHz**, closely matching the theoretical 1.59 kHz. This is shown in the Bode plot in Figure 4. The transient analysis at 10 kHz (Figure 3) showed a peak output voltage of 2.51 V, differing from the steady-state theoretical value of 1.57 V.

#### 4.1.2 Experimental Results

The experimental results for the passive filter, shown in Figure 5 and Table 1, did not conform to the expected low-pass behaviour. Instead of a flat passband, the gain was highly attenuated at low frequencies and exhibited a resonant peak around 4 kHz.

### 4.2 Variable High-Pass Filter Simulation Results

The simulation results for the variable high-pass filter are shown in Figure 6. The plot displays three distinct frequency response curves corresponding to the potentiometer settings for 'RES1'. As predicted, increasing the resistance shifts the cutoff frequency lower.

The -3 dB cutoff frequencies were measured directly from the PSpice simulation for each setting:

- 'RES1' = 1  $\Omega$ : Cutoff frequency = **3.376 kHz**
- 'RES1' = 5 k $\Omega$ : Cutoff frequency = **1.941 kHz**
- 'RES1' = 10 k $\Omega$ : Cutoff frequency = **1.376 kHz**

The simulated adjustable range is therefore approximately 1.4 kHz to 3.4 kHz. The slope of the filter's stopband is approximately +40 dB/decade, which is characteristic of a second-order filter [2].

## 5 Discussion

The investigation of the passive low-pass filter showed strong agreement between theory and simulation. The simulated cutoff frequency of 1.6 kHz matched the theoretical 1.59 kHz. In stark contrast, the experimental results diverged significantly, exhibiting resonant behaviour likely caused by parasitic inductance from the breadboard setup, which formed an unintended RLC circuit.



For the active high-pass filter, the simulation successfully demonstrated the intended functionality of an adjustable cutoff frequency. However, the simulated frequency range of **1.4 kHz to 3.4 kHz** differs notably from the ideal theoretical range of **0.54 kHz to 2.2 kHz**. This discrepancy is likely due to the use of the non-ideal ‘LM741’ op-amp model in the simulation. The simple theoretical formula assumes an ideal op-amp with infinite gain and bandwidth. The LM741, being a real-world component, has limitations such as a finite gain-bandwidth product, which alters the filter’s response and shifts the cutoff frequencies higher than the ideal calculation predicts. This highlights that while ideal formulas are excellent for initial design, accurate simulation with realistic component models is necessary to predict true circuit performance.

## 6 Conclusion

This investigation successfully validated the theoretical model of an RC low-pass filter through PSpice simulation and further explored the design of an active variable high-pass filter. The primary objectives were met, as the ideal behaviour of the passive circuit was accurately predicted by theory and confirmed by simulation. The design of the variable high-pass filter successfully demonstrated how active components can be used to create adjustable and robust circuits for applications like audio control [3].

The passive filter experiment highlighted the critical impact of real-world non-idealities, where parasitic effects fundamentally altered the circuit’s behaviour. Similarly, the active filter simulation showed that the performance of even a well-designed circuit is influenced by the limitations of its components. Ultimately, this lab illustrates that while theory provides a foundation and simulation predicts behaviour, understanding the gap between ideal models and physical reality is essential for successful electronic engineering.

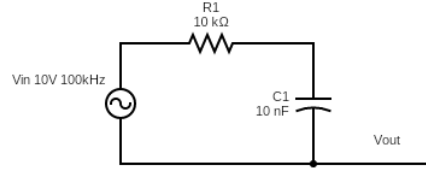


Figure 1: Schematic of the Low-Pass Filter circuit.

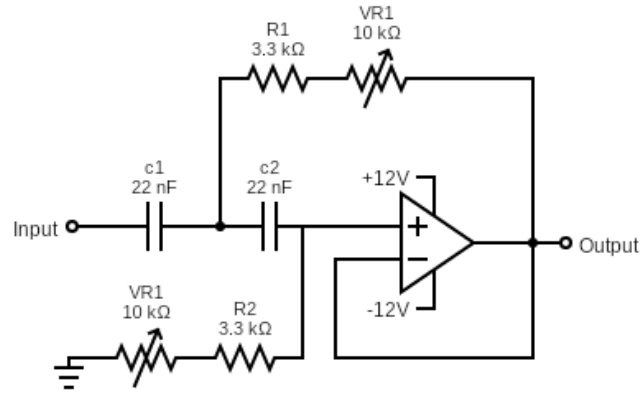


Figure 2: Schematic of the designed Variable High-Pass Filter.

Table 1: Selected Experimental Data from Picoscope Measurements for the LPF.

| Frequency (kHz) | Vin (mV) | Vout (mV) | Gain (dB) |
|-----------------|----------|-----------|-----------|
| 0.5             | 300      | 5.3       | -35.06    |
| 1               | 560.5    | 45.89     | -21.74    |
| 1.5             | 766.7    | 124.3     | -15.80    |
| 2.5             | 935.7    | 261.6     | -11.07    |
| 4               | 666.1    | 247.1     | -8.61     |
| 8               | 661.8    | 130.3     | -14.12    |
| 10              | 661.1    | 105       | -15.98    |
| 30              | 917.7    | 26.73     | -30.71    |

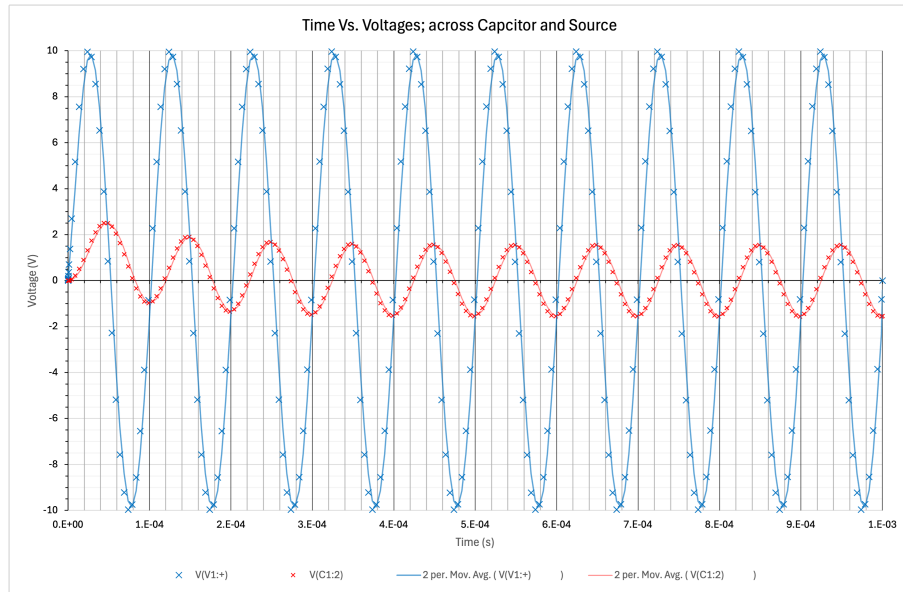


Figure 3: Simulated source voltage (input) and capacitor voltage (output) vs. Time at 10 kHz.

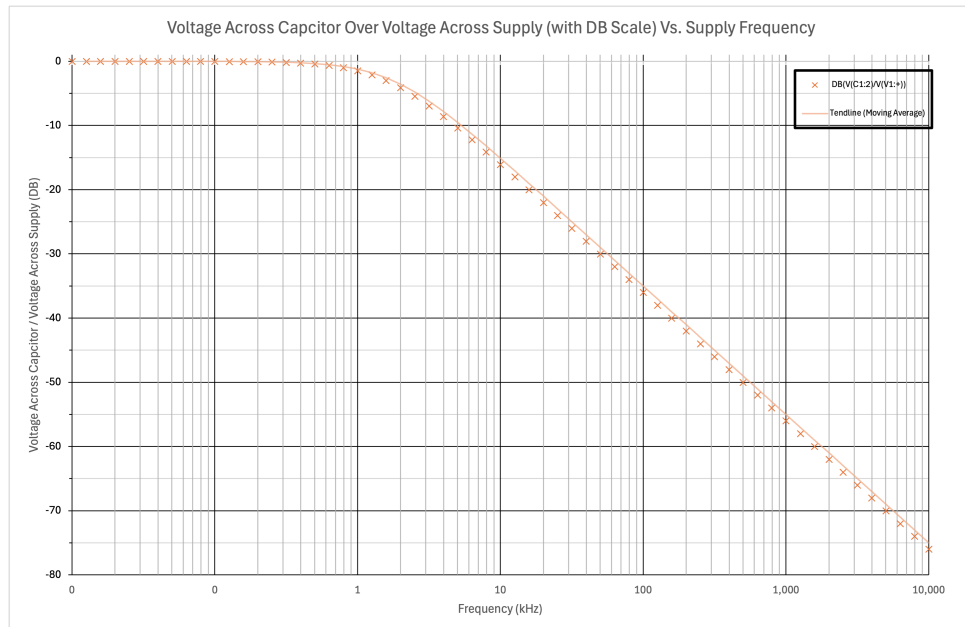


Figure 4: Simulated frequency response of the low-pass filter (dB gain scale).

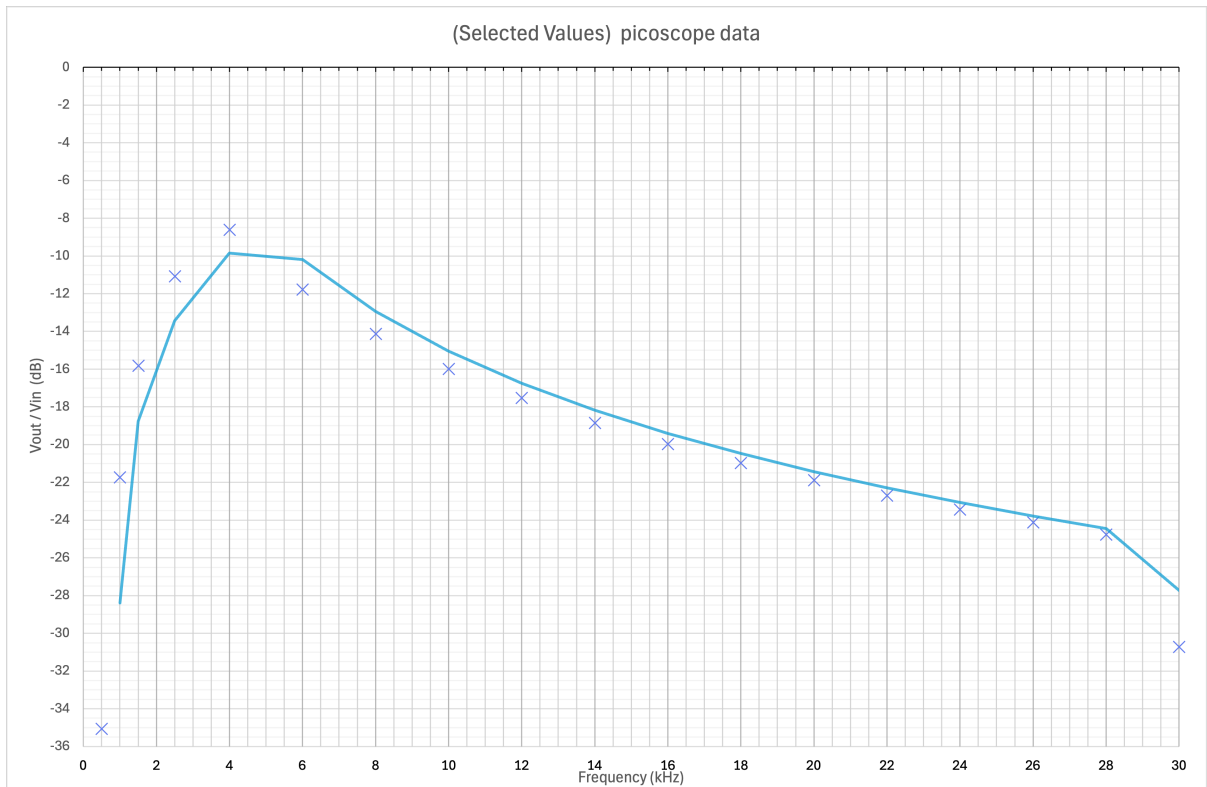


Figure 5: Experimental frequency response from Picoscope data for the passive LPF.

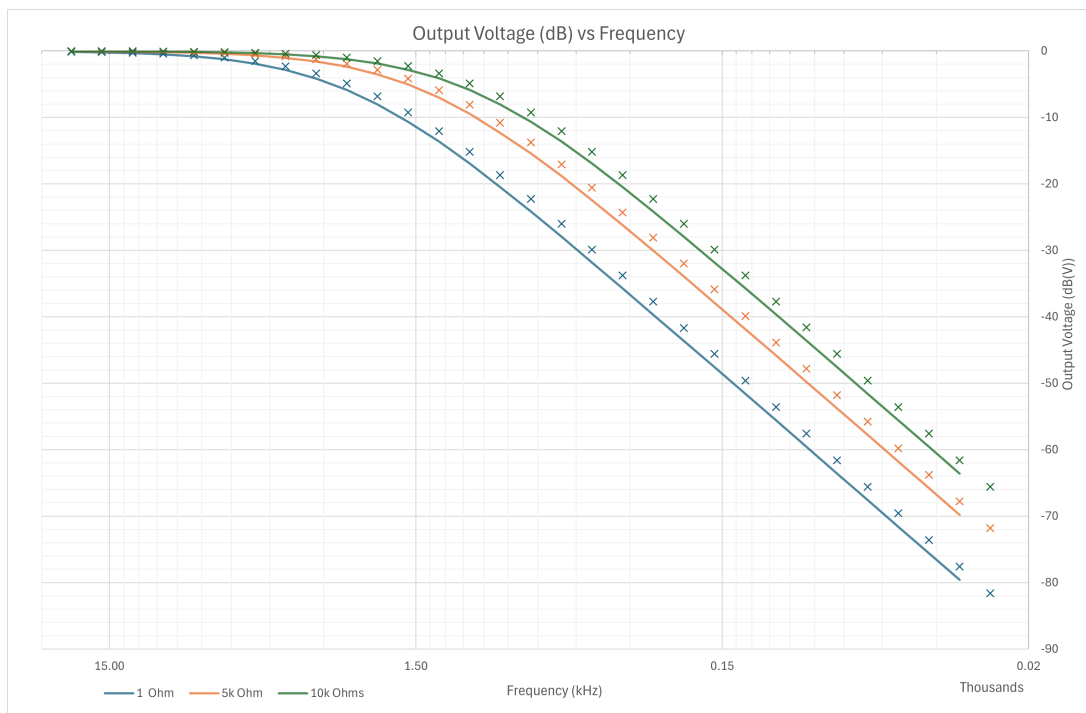


Figure 6: Simulated frequency response of the variable high-pass filter. The curves from left to right correspond to RES1 values of 1  $\Omega$ , 5 k $\Omega$ , and 10 k $\Omega$ .

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